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Development Of An Integrated Solution For Multi Scroll Compressors With Wet Vapor Injection

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Development of an Integrated Solution for Multi Scroll Compressors with Wet Vapor Injection

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ABSTRACT

Extensive use of Heat Pumps is essential to meet European 20-20-20. Reversible air-to-water heat pump systems have to operate at high efficiency levels on a wide operating range to be an economical alternative to the traditional heating and cooling systems. This paper presents the advantages, the control and the implementation of multi vapor injected scroll compressors systems in commercial heat pump water heater application. Enhanced Vapor Injection (EVI) technology allows both performance and reliability improvement across the compressors operating area, especially at low ambient temperatures. Wet Vapor Injection allows extending compressors operating range at very low ambient and high condensing temperatures. The development of a solution integrating injection capable scroll compressors, expansion valves and wet/vapor injection control system is presented in this paper.

1. INTRODUCTION

The European commission has recognized air, water and ground as renewable energy sources and has indicated heat pumps as the most effective technology to make use of them. As a consequence, energy performance requirements and performance labeling schemes for heat generators are defined in terms of seasonal primary energy efficiencies. ErP (Energy related Products) directives define the methodology and reference normative by which obtaining the seasonal primary energy efficiency value (η%), which is directly related to the seasonal efficiency of the heat pump measured through the EN14825. New energy performance requirements concern heat generators with rated output until 400kW. Energy performance labels are defined only for products with rating capacity below 70 kW and will be in application in 2015.

Today, seasonal performance requirements are also being defined for cooling products (including chillers) with rated output below and above 400kW.

In Europe, a very large portion of today's heating market is the replacement of existing older type heating systems, representing a large potential for heat pump applications. Most of time, existing heating systems are designed to operate with high temperature hot water (e.g. radiators operating with hot water at 60°C and above). Although several heat pump concepts exist, the air-to-water heat pump which uses ambient air as heat source is the most promising heat pump concept for a replacement of existing fossil fuel heating systems.

However, such application presents the most difficult operating conditions for the operating heat pump, since in this case particularly high water inlet temperatures are combined with a substantial variation of the heat source temperature (typically from -15°C to 15°C). In this case, the design point for a compressor is the extreme point of this application, which is a particularly low evaporating temperature in combination with a high condensation temperature as shown in Figure 1 (Liegeois and Winandy, 2008).

These operating points can be achieved when using dedicated scroll compressors. Within the last years, many heating optimized scroll compressors, such as ZH**K1P compressors illustrated in Figure 1, have been released. Main design changes include scroll set design, floating seal design and the addition of a dynamic discharge valve (Liegeois and Winandy, 2008).

Substantial increase of performance and operating range (e.g. ZHI**K1P compressors shown in Figure 1) have been demonstrated by using heating optimized scroll compressors equipped with vapor injection technologies (Winandy and Hundy, 2008).

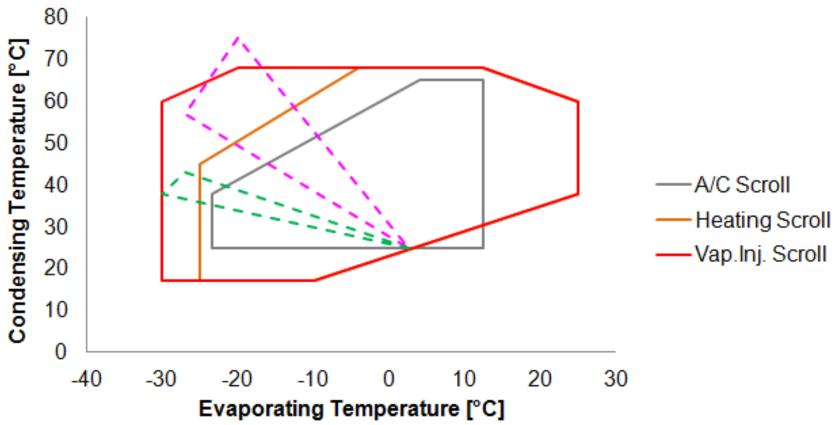


Figure 1: Typical Compressor Operating Map of Air-Source Heat Pump

In 2012, heating optimized high efficiency variable speed scroll compressors, featuring vapor injection and wet-vapor injection, have also been released. Those compressors are qualified with R410A refrigerant and are controlled by an Emerson drive (Dardenne et al., 2014). More recently, an integrated "Refrigerant Module for Heating" (RMH) has been developed using this technology. This is a refrigerant circuit designed for use in split air-to-water heat pump applications, where the evaporator is located outdoors. RMH integrates the aforementioned vapor injection variable speed compressor, its drive, the indoor refrigerant circuit (i.e. economizer, liquid receiver…) and its "Refrigerant Circuit Controller" (RCC). The compressors and solutions mentioned above are mainly dedicated to the residential sector and cover a capacity range from 4kW to 23kW (for an operating condition of -6.7/50°C). Indeed, the use of heat pumps for space heating has already a quite long tradition in the European residential sector.

Today, heat pumps are being more and more considered for commercial applications too. Thus, the range of vapor and wet injection capable (ZHI**K1P) compressors has been extended till 46kW (at -6.7°C/50°C) heating capacity (Vazquez and Zamana, 2013). Tandems of these heating optimized compressors are now being used in commercial air-to-water heat pump units with rated output until 200kW.

This paper presents the development of an integrated solution for multi-scroll applications with vapor and wet injection. Benefits and application of vapor injection and wet injection technologies are discussed hereunder.

During the development phase, testing has been conducted on an economized cycle equipped with two vapor injected scroll compressors installed in parallel in order to prove that this solution was performing in terms of efficiency, reliability and vibrations. Expansion valves selection has been refined and controller software has been fine-tuned to allow wide operating range and to ensure control reliability and stability in both vapor and wet injection operating modes. Special attention has been paid to the design of the injection line to ensure good flow distribution (in wet vapor injection operation) and to keep vibration levels below the limit.

2. INJECTION TECHNOLOGY

2.1 Vapor Injection

One of the most important ways to optimize the seasonal efficiency of an Air-to-Water heat pump system is to limit the need of any back-up heater by cold outdoor temperature. With a standard scroll compressor, the heating during cold period is generally limited by the discharge temperature limit of the compressor, especially when high water temperature is requested.

Vapor injection technology, commonly called EVI, can push the compressor operating limits by cooling down the refrigerant gas at an intermediate level of the compression through an additional injection stub on the compressor. Figure 2 shows the injection ports located symmetrically in the scroll compression path as well as the upper part of the compressor where it can be seen the injection tube from the shell injection port to the scroll set (Winandy and Hundy, 2005).

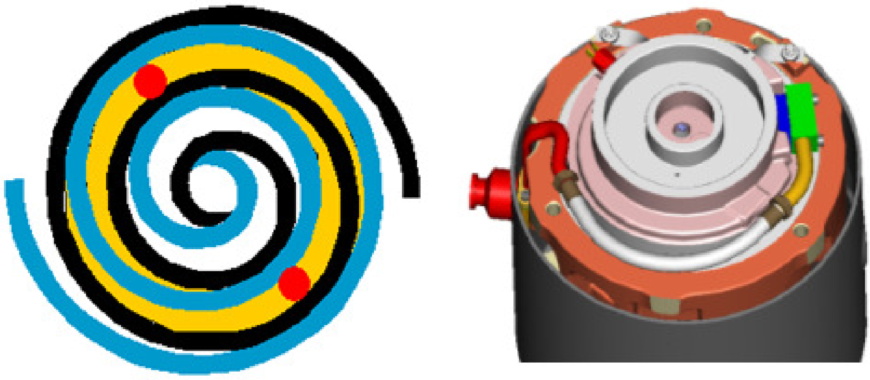


Figure 2: Vapor-injected scroll compressor

The vapor injected scroll compressor cycle is similar to a two-stage cycle with interstage cooling, but accomplished with a single compressor as shown in Figure 3. The high stage is accomplished by extracting a portion of the condenser liquid and expanding it through an expansion valve into a counterflow brazed-plate heat exchanger acting as a sub-cooler. The superheated vapor is then injected into an intermediate vapor injection port in the scroll compressor. The additional sub-cooling increases the evaporator capacity by reducing its inlet enthalpy (Beeton and Pham, 2003).

In addition to enlarging the compressor operating envelope, this cycle offers the advantages of a higher heating capacity and a better COP than a conventional cycle. Both the heating capacity and the COP improvement are proportional to the temperature lift and this technology offers best results at high condensing operation where capacity and efficiency are most needed. At -6.7/50°C, for a given displacement, heating capacity increase and COP increase due to the use of vapor injection may reach, respectively, 20% and 10% (Beeton and Pham, 2003).

The control of the injection line expansion valve is relatively straightforward and aims at maintaining the injection superheat setpoint around an optimal value (typically 5K to 7K).

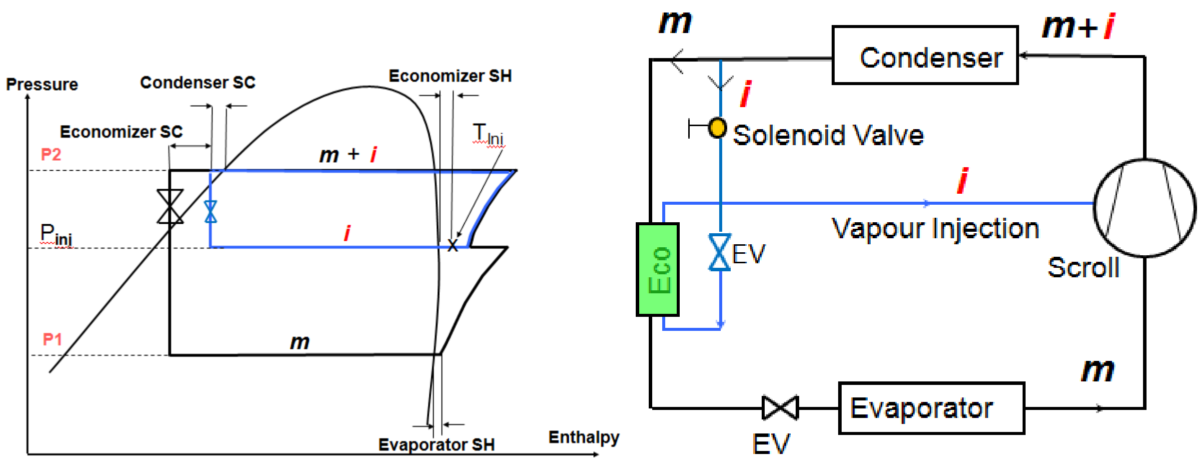


Figure 3: Vapor Injection Technology P/h Diagram and Circuit Schematic

2.2 Wet-Vapor Injection

Additional gas cooling and therefore even larger operating envelope can be obtained with liquid injection. The additional cooling liquid can be injected along with the gas through the injection stub. This is called wet-vapor injection. Figure 4 shows the p/h diagrams of wet vapor injection and its operating envelope benefit. Note that wet injection is carried out only at the level of the intermediate injection port. The main evaporator superheat should remain positive enough to avoid liquid droplets at the compressor suction port.

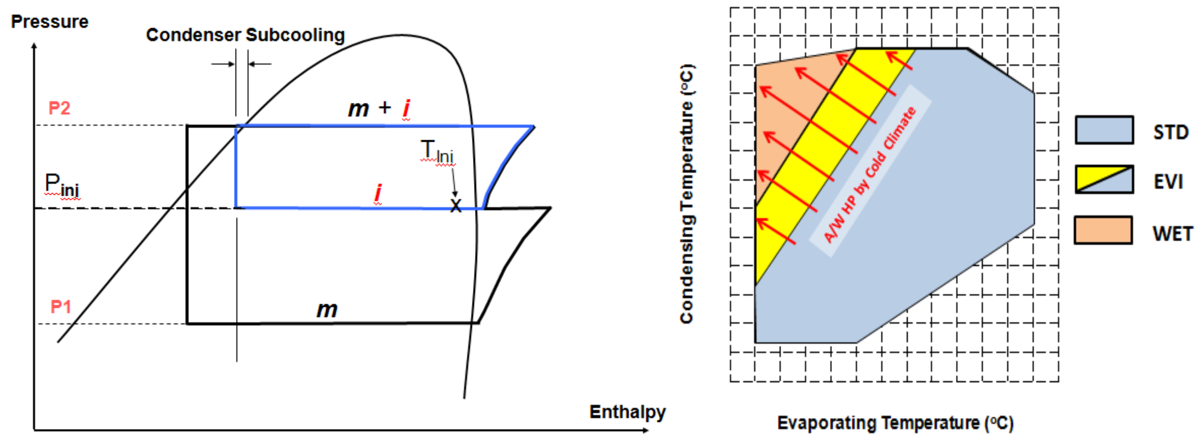


Figure 4: Wet-Vapor Injection Technology Ph Diagram and Compressor envelope extension

Whilst vapor injection control is similar to a classical superheat control, the wet injection control is slightly different. In such operating mode, injection gas temperature control is not anymore applicable and the injection line expansion valve is controlled, according to a patented, in order to maintain the compressor discharge temperature below a certain limit.

3. DEVELOPMENT OF AN INTEGRATED SOLUTION

An integrated solution relying on injection capable scroll compressors (ZHI*K1P) and dedicated to commercial heat pump applications has been developed. This solution includes (Figure 5):

- A tandem of ZHI**K1P compressors (for a heating capacity range from 36 kW to 92 kW at -6.7/50°C) equipped with "top cap mounted" discharge gas temperature sensors,
- Adapted injection flow temperature and pressure sensors,
- Selected Solenoid Valves for injection interruption in non-running compressor(s),
- Selected EXM/L unipolar expansion valves,
- An EXD-TEVI driver for vapor and wet injection control,
- Guidelines for the suction, discharge and injection lines piping design,
- Guidelines for the selection of the economizer plate heat exchanger.

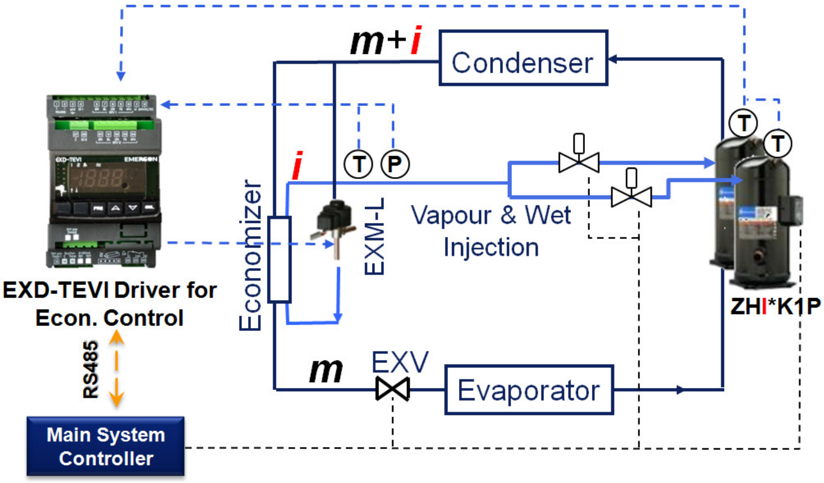


Figure 5: Integrated Solution for Injection Capable Scroll Compressors Tandems

3.1 Compressors

An important topic when considering the parallel operation of scroll compressors is the design of suction and discharge lines. In the present case, compressor suction and discharge lines designed for the paralleling of similar non-injection compressors have demonstrated good results in terms of gas and oil distribution and collection and have been used for the present application.

However, a particular attention has been paid to the design of the less-standard injection line. Indeed, like the other piping parts, the injection line design has to ensure reliable operation of the tandem of compressors in terms of vibrations but also to ensure even flow distribution in both vapor and wet injection modes.

3.2 Sensors

As mentioned above, injection capable ZHI*K1P compressors are equipped with top-cap discharge gas temperature sensors (Figure 6). These temperature probes are installed in a "sensor pocket" located on top of the compressor cap, covering the gas discharge area in order to avoid variable effects of sensor position and fixing, discharge pipe conduction, etc.

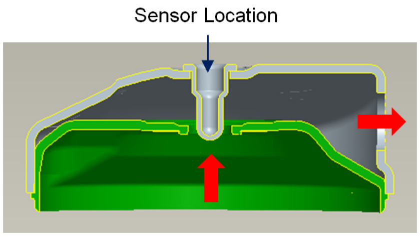


Figure 6: Top Cap Temperature Sensor Pocket

Such sensors are able to give a more accurate measurement (in terms of static offset and dynamic reactivity) of the discharge gas temperature than discharge line surface temperature sensors used in standard installations. Accurate and fast discharge temperature measurement is required to ensure reliable compressor operation during wet injection operation. Other sensors are typical temperature sensors and pressure sensors.

3.3 Valves and Control

Solenoid valves have to be installed on the injection line to interrupt the injection flow in the pipe connected to a non-running compressor. Indeed, in part load operation, when only one compressor of the tandem is running, a partial by-pass would occur through the injection ports of the non-running compressor. Such by-pass could degrade system performance and cause undesirable reverse rotation of the non-running compressor.

Solenoid valves considered for this type of application are generally “normally closed pilot operated solenoid valves”. A minimal operating-pressure differential (minOPD) is required for the valve piston to stay open (Maier, 2007). An oversizing of the valve could result in a valve that not open or fail to stay open in some low-flow conditions. On the opposite, an undersized valve would generate undesirable high pressure drops at high injection flow conditions.

Standard valves selection equations (relying on valves characteristics such as Kv-value; Emerson Process Management, 2014) have been implemented in EES (F-Chart, 2014) and used to compute the theoretical pressure differential in the valve across the compressor operating map allowing to refining the selection of the solenoid valves for the whole range of compressors. Flow calculations have been done considering the following reference conditions: 5K suction gas superheat, 5K liquid sub-cooling, 5K injection superheat and 5K economizer approach.

In the present case, solenoid valves have been selected in order to keep the pressure drop below an acceptable level and to ensure proper valve opening across the major part of the envelope. Injection flow may be interrupted at low Pressure Ratio (PR) conditions (i.e. high evaporating and low condensing temperatures), when vapor injection has very reduced impact on compressor performance (Figure 7).

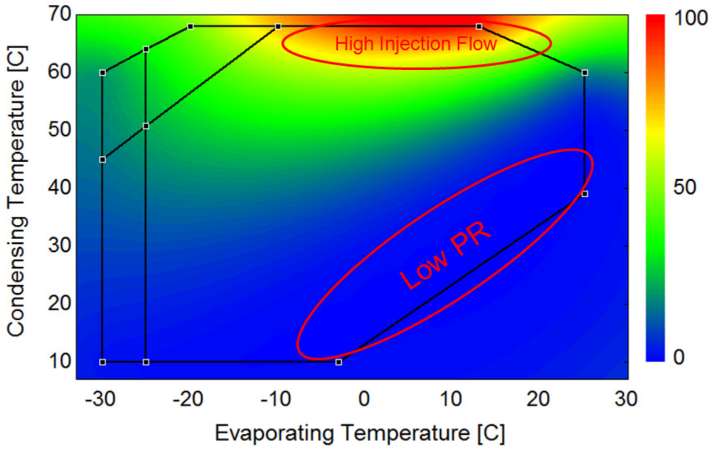


Figure 7: Computed relative solenoid valve pressure drop (% of max) across compressor operating map computed for 5K-5K-5K operation

The EXD-TEVI driver ensures injection EXV control across the whole compressor operating map, for both vapor and wet injection operation. Auto-adaptive PID control is used in vapor injection mode. The transition and the operation in wet-injection mode are handled by means of a fine-tuned algorithm based on fuzzy-logic control. Such control ensures reliable and smooth control of the system in both operating modes.

Injection flow variation range across compressor operating map also has a direct impact on the selection of the expansion valves. Proper operation of unipolar expansion valve is generally guaranteed from approximately 7% to 100% capacity ratio. Theoretical expansion valve capacity ratio has been calculated considering and used to refine the selection of expansion valve for the whole range of compressors. For larger capacities, two expansion valves may be installed and controlled in parallel by the EXD-TEVI driver to cover the whole compressor operating map. While extending the application range of the considered valves, such installation has the advantage of increasing control resolution.

4. LABORATORY TESTING AND DESIGN QUALIFICATION

4.1 Vibrations Testing

One of the major challenges of the considered design is to ensure reliable operation of the system in terms of vibrations. To this end, strain gauge tests have been performed at various conditions all along the injection line (Figure 8).

Relatively high vibration levels may be encountered on the injection line at high flow conditions in vapor injection mode (i.e. at high evaporating and high condensing temperatures, around "High-Load" condition). Highest vibration levels were measured around the tee-junction where the injection flow is split in two flows supplying the two compressors.

Piping design has been adapted in order to keep piping stress below a maximal piping resistance reference limit. A first improvement consisted in installing the solenoid valve in a horizontal position in order to avoid any undesired balancing movement and allowing easy fixation/support (Figure 8). Adding supplemental supports/straps along the injection line was the simplest and most efficient solution to keep vibrations under control.

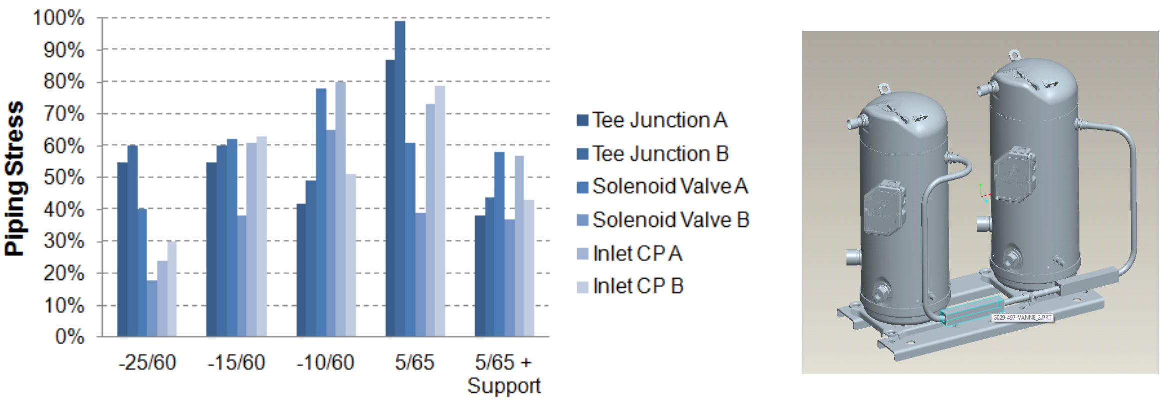
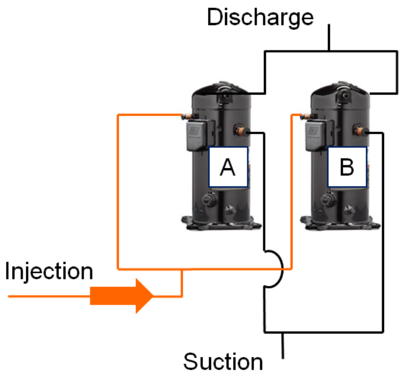


Figure 8: Injection Line Strain Gauge Tests Results (Left) and 3D CAD of final injection piping (Right)

4.2 Vapor and Wet Injection Operations

A second major challenge of the present design is to ensure stable and balanced injection flow distribution in both wet and vapor injection mode, all across the compressors operating range. The two compressors are labeled "A" and "B" depending on their position in regard with the injection line main direction.

As shown in Figure 9, operation in vapor injection mode at -10/60°C (i.e. with high injection-to-suction mass flow ratio) is stable. The injection SH is maintained very close to the setpoint (7K) and the valve opening, as well as compressors discharge gas temperatures (or Discharge Line Temperature, "DLT"), are stable all along the test. The very small discharge temperature difference can be easily explained by compressor production variability and is in line with tests realized in single operation.



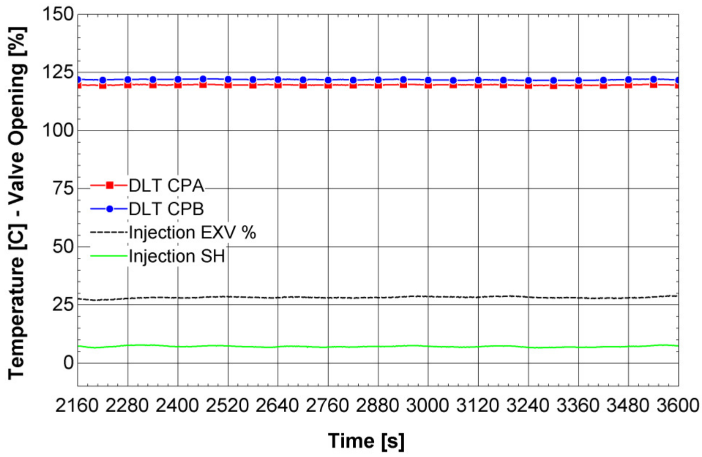
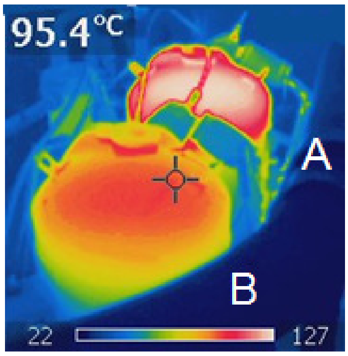


Figure 9: Vapor Injection Operation at -10/60°C

In wet injection operation, at -25/64°C, results are very different. The injection expansion valve is not anymore controlled to maintain a constant injection superheat but to maintain the compressors discharge temperatures below a given limit of about 135°C. No particular issue was encountered in single operation and both compressors performed in accordance with single compressor performance data.

In Tandem operation, after a few minutes of operation in wet injection mode, a significant unbalance maybe noticed between the two compressors discharge temperatures (Figure 10). After about 10 minutes of operation, this unbalance was approximately 30 K.



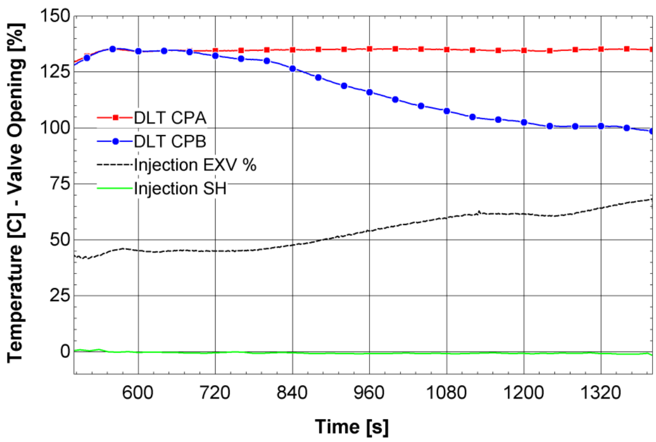


Figure 10: Discharge Temperature Unbalance during Wet-vapor Injection Operation at -25/64

It appears that the compressor "A" is not properly cooled by the wet injection while compressor "B" is "overcooled" (Figure 10). Meanwhile, expansion valve opening, and so, the flow liquid fraction, keep on increasing because of controller operation. This unstable operation was noticed only across the wet-injection area of the compressor map, with different levels of amplitude depending on the conditions (discharge temperature unbalance varying between 8K and 35K) but generally leading to compressor trip (usually because of compressor overheating).

Bad wet-vapor (i.e. two-phase) flow distribution was considered as a possible explanation of such behavior. Indeed, depending on the piping layout, one of the two compressors may take in a major part of the liquid droplets while the other compressors may take in much more high quality mix. This results in an "overcooling" of the first compressor and a not efficient cooling on the second one. As a reaction, the controller, considering the discharge temperature of the hottest controller, keeps on opening the expansion valve.

This explanation was confirmed by CFD modeling (done in ANSYS-Fluent, 2014) of the flow distribution in the injection tee-junction (Figure 11). Measured values of piping inlet flow and outlet pressures were used as boundary conditions and various conditions and flow liquid fractions were considered. The results were in good accordance with experimental observations: the compressor located in line with main flow direction was taking in more liquid than the other one.

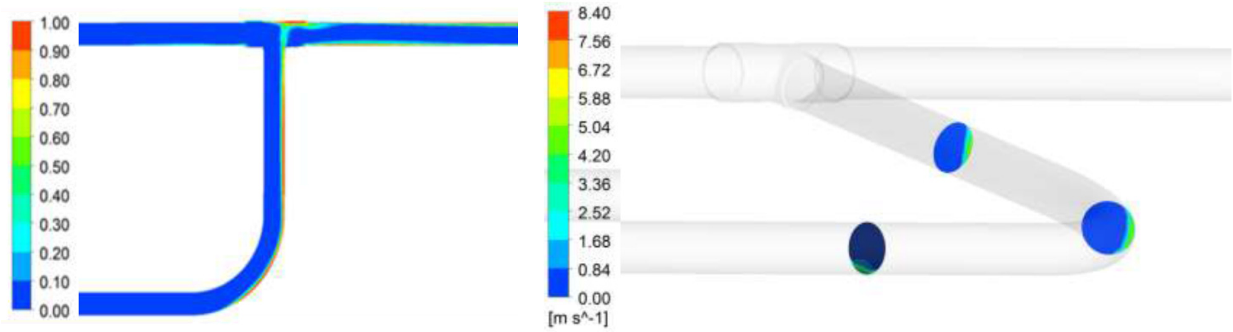


Figure 11: CFD Simulation of Injection Flow Distribution in Wet-Vapor Injection Operation (Left: liquid volume fraction; Right: liquid superficial velocity)

A reliable solution consists in adapting the injection piping to improve the two-phase flow distribution. Increasing the turbulences upstream of the flow separation allowed to obtaining a more homogenous distribution of the liquid droplets in the flow and a better distribution. Many qualification tests were realized in steady-state and transient operation in order to validate this final design and were successful (Figure 12).

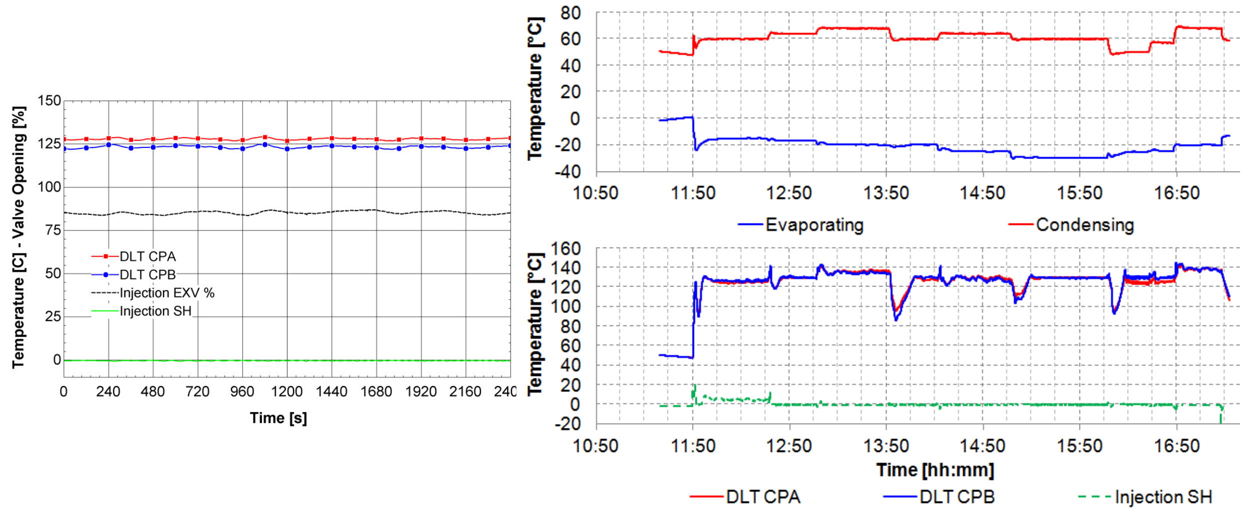


Figure 12: Stable and Balanced Wet-vapor Injection Operation at -25/64°C (Left) and in transient operation (Right)

5. CONCLUSIONS

In Europe, Air-to-Water heat pump using ambient air as heat source are among the most promising solutions when considering heating system replacement in residential and commercial buildings. However, this system presents the most difficult operating conditions for the operating heat pump, since in this case particularly high water inlet temperatures are combined with a substantial variation of the heat source temperature.

These operating points can be achieved when utilizing dedicated modifications to standard scroll compressors. Vapor Injection offers a versatile means for improving efficiency and extending the operating map of scroll compressors for water heating applications. More efficient compressor cooling, and so, further operating range extension, can be obtained by injecting additional liquid droplets in wet injection operation.

The development of a solution integrating injection capable scroll compressors, expansion valves and wet/vapor injection control system and dedicated to commercial heat pump applications was presented in this paper.

Testing has been conducted on an economized cycle equipped with two vapor injected scroll compressors installed in parallel in order to prove that this solution was performing in terms of efficiency, reliability and vibrations.
Expansion valves selection has been refined and controller software has been fine-tuned to allow wide operating range and to ensure control reliability and stability in both vapor and wet injection operating modes. Special attention has been paid to the design of the injection line to ensure good flow distribution (in wet vapor injection operation) and to keep vibration levels below the limit.

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